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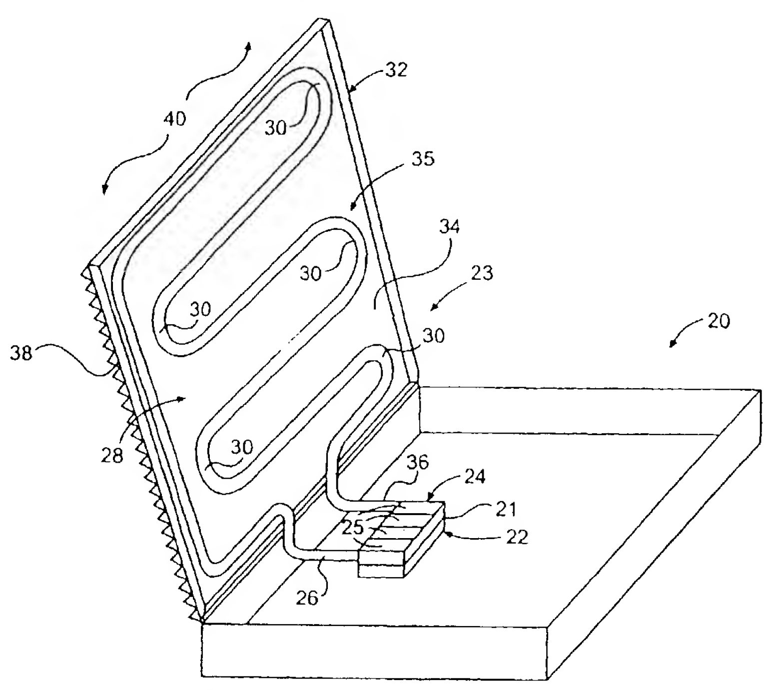
(54) Title: HIGH-EFFICIENCY COMPUTER THERMAL MANAGEMENT APPARATUS AND METHOD



(57) Abstract: A package (21) containing an electronic component (22) and having a heat removal system (23).

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HIGH-EFFICIENCY COMPUTER THERMAL MANAGEMENT APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

This application is a Continuation-In-Part of U.S. Patent Application S/N 09/627,163, filed July 27, 2000, the contents of which is incorporated herein by reference in its entirety.

1. Field of the Invention

This invention is directed generally to a cooling apparatus for a heat-generating electronic component and more particularly is directed to a cooling apparatus and method for an integrated circuit, such as a microprocessor, that generates a relatively large amount of heat. In one field, such a heat generating integrated circuit is installed into a package that has a low or minimal heat removal capability, such as a portable electronic device, including a notebook computer and a telecommunication device.

2. Background of the Invention

Since the advent of high density integrated circuits in general, and microprocessor technology in particular, dissipation of waste heat generated in a microprocessor has been of critical concern. The earliest microprocessors dissipated waste heat by direct thermal radiation into an atmosphere surrounding the microprocessor.

As microprocessor component densities have increased and as processing speeds have increased, the amount of waste heat generated in the microprocessor has increased exponentially with a concomitant need to increase the rate at which the waste heat can

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A. CLASSIFICATION OF SUBJECT MATTER

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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,842,513 A (MACIASZEK et al) 01 December 1998, see entire document.	1-40

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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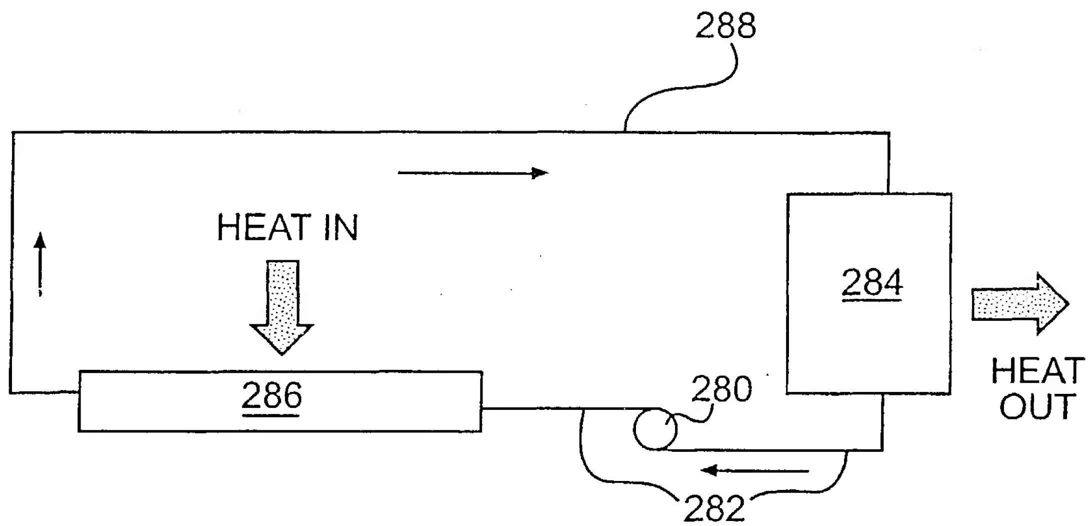


FIG. 13

be dissipated. In addition, with the advent of laptop computers, notebook computers, hand held computers, and other portable electronic equipment, the ability to use space or a fan to dissipate the heat became impossible.

Some second generation microprocessors were equipped with a heat-sink in direct thermal communication with the microprocessor. Others used an indirect thermal coupling between the heat source and the heat sink. The heat-sink provided an increased surface area over which the waste heat could be dissipated and thereby increased the amount of waste heat that could be dissipated in a given period of time. These heat-sinks, as in earlier microprocessors, dissipated the waste heat through direct thermal radiation into the atmosphere. Later second and third generation microprocessors were often equipped with a fan to provide a forced air convection current over a surface of the microprocessor and thereby remove the waste heat. In yet other instances both the heat-sink and the fan have been used in conjunction with each other. An example of a heat sink for a portable electronic device is described in the Furukawa et al. patent, U.S. Patent No. 5,937,936. Other cooling apparatus for electronic components and the portable devices using such components are described in the Esser et al. patent, U.S. Patent No. 6,041,850; and the Larson et al. patent, U.S. Patent No. 5,560,423. Each of these three U.S. patents are incorporated in their entirety herein by reference.

Exacerbating the need to facilitate heat dissipation from microprocessors has been the increased frequency with which high

speed, high capacity microprocessors have been incorporated into smaller and smaller portable devices such as notebook computers. Due to their small size, these portable devices frequently are incapable of accommodating large heat-sinks or fan-forced convection cooling systems. Further exacerbating the problem and due to both the device's portable nature and consumer concerns respecting useful life between successive recharging of batteries, these devices must reserve a maximum of available battery capacity for the device's primary operations instead of availing battery capacity for ancillary functions such as microprocessor cooling.

Within recent years, and further confounding the heat removal problem, newer microprocessor speeds have been at least doubling each year in relation to speeds of the year before. Similarly, component densities within newer microprocessors have likewise been increasing at an explosive rate. Faster speeds and higher component densities each increase the rate at which electrical energy is converted into thermal energy in these devices and thereby further increase the need for an improved thermal management system.

The next generations of high-speed, 64 bit, 132 bit and greater bit count microprocessor chips will not only incorporate unprecedented component densities, but will require thermal dissipation rates on an order of magnitude or more greater than present cooling systems currently provide. The dissipation of these heat fluxes is beyond the capacity of prior art passive direct radiation and fan-forced convection cooling systems.

While the prior art is replete with active cooling and heat removal systems, very few are suitable for a portable computer device or other small, compact, portable electronic device which generates a relative significant amount of heat. An active cooling and heat removal system is one which utilizes a movable substance to receive heat from one part of a heat system, such as a heat generating electronic circuit, and then physically move the substance and deliver the heat to another part of the heat system, such as a heat sink. The heat sink can simply be a remote part of the environment. An example of a prior art active cooling and heat removal system is a fan. Some commonly used movable substances include air, "freon," oil, and chilled water. In contrast, an example of a passive cooling and heat removal system would be a heat sink physically mounted to an integrated circuit.

In all cases, however, such active cooling and heat removal systems require a motive system to physically move the moving substance from one part of the heat system to another. For example, in the prior art, it is known to use pumps and gravity. Another such motive system, however, is also known and utilizes a capillary-pump theory. A full description of this theory and the operation of such a system is described in Transient Performance of a Capillary-Pumped, Two-Phase Heat Transport System, Tinari, P.D. (Dec. 1989), Ph.D. Thesis, von Karmin Institute for Fluid Dynamics, University Library of Brussels, Rhode St. Genese, Belgium, a copy of which is also available over the Internet at the address of "sway.com/~pacific." This reference demonstrates the

knowledge of those skilled in the art and is also incorporated herein by reference in its entirety as background material.

As is known to those skilled in the art, the capillary-pump apparatus of the prior art includes heat pipes to transport and conduct the working fluid. Such heat pipes include wicks with a uniform pore size over the entire length of the heat pipe.

The traditional design of a capillary pump uses a wick made of various porous materials in order to produce a stable interface at which to produce a pressure rise in the vapor phase. The presence of a capillary wick can, however, impose a large pressure drop on the refrigerant fluid flowing through a capillary pump evaporator.

However, this poses a dilemma in that while the pressure rise due to capillary forces in the evaporator portion of the heat pipe is maximized by using a small-pore wick, it is also desirable to minimize the pressure drops due to fluid flow returning from the condensing portion by using a large-pore wick.

Prior art heat pipes offer a number of advantages over single phase systems, but they have intrinsic limits in the rate at which they can remove waste heat because of a tendency of their wicks to dry out under high heat loads.

Accordingly, there exists a need for a high-efficiency miniature heat-transport apparatus that requires no externally applied power source; that can derive its operating power directly from the waste heat energy it is removing; that is compact and light weight enough to be incorporated into portable devices such as notebook computers; and that has a thermal dissipation rate on

an order of magnitude or more greater than present cooling systems currently provide.

SUMMARY OF THE INVENTION

The present invention meets the above mentioned needs for an active system for removing waste heat from heat sources installed in small portable devices with limited electrical power, such as a microprocessor of a notebook computer. The present invention provides a highly efficient, miniature heat-transport apparatus that requires no externally applied power source. It can derive its operating power directly from the waste heat energy it is removing, and it is compact and light weight enough to be able to be incorporated into portable devices such as notebook computers. It also has a thermal dissipation rate on an order of magnitude or more greater than present cooling systems currently provide.

In accordance with one embodiment of the present invention, a high-efficiency capillary pumped two-phase heat transport apparatus is incorporated. This apparatus transports waste heat generated by an electronic component such as a microprocessor or other heat-generating integrated circuit of a portable device to a heat exchanger in thermal communication with an atmospheric heat-sink located outside the portable device where the waste heat can be dissipated.

According to a particular two-phase capillary-pumped heat transfer apparatus of the present invention, heat is transported by latent heat of vaporization of a working refrigerant fluid. However, it is also desirable to minimize the pressure drops in the

apparatus. In a specific embodiment of the present invention the pressure drops due to fluid flow returning from the condensing portion is minimized by using a large-pore wick. Also a specific capillary-pump apparatus component of the present invention differs from a heat pipe in that condensed refrigerant fluid is returned to the evaporator via a different pipe than the pipe used to return the vapor. Moreover, while a heat pipe contains a wick throughout its entire length, the capillary pump has a wick only in its evaporator. Accordingly, in a preferred embodiment of the present invention the capillary pumping function of the wick is separated from the condensing and liquid transport functions.

The capillary-pumped apparatus of the present invention in a particularly preferred embodiment comprises a closed loop having diverse evaporators, condensers, gas traps, valves, liquid and vapor connective transport pipes, an accumulator that can be arranged in various configurations; and a working two-phase refrigerant fluid contained therein. In the evaporating section heat enters by thermal conduction from a heat source in contact with one or more cold plates connected in parallel. Each cold plate has a plurality of capillary pumps connected thereto. In a preferred embodiment of the present invention the evaporator is placed in direct physical contact, sometimes referred to being in intimate thermal contact, with a microprocessor heat source. Heat is conducted from the microprocessor to the evaporator wherein a liquid phase refrigerant fluid is caused to undergo a phase change to a vapor phase and thereby effectuate a pressure increase and

provide the driving force needed to circulate the refrigerant fluid.

Capillary forces in the evaporators provide the requisite pressure to drive the vapor phase refrigerant fluid through the loop. The vapor phase refrigerant fluid from the evaporator flows through a vapor pipe to the condensing section which, in the preferred embodiment, is located in a cover of a notebook computer. In a particularly preferred embodiment, the condenser is located under a metal plate in the cover of the notebook computer and is exposed to an ambient atmospheric heat sink. In another particularly preferred embodiment the condenser can be connected to external sidewalls of the notebook computer's case. At the condenser the heat is dissipated to the heat sink which, in turn, results in the vapor phase refrigerant fluid undergoing a second phase change whereby it condenses back to a liquid phase and thereby simultaneously effectuates a reduction in pressure. The liquid phase refrigerant fluid then flows back to the evaporator through a liquid return pipe to complete the cycle. The capillary-pumped thermal management apparatus of the preferred embodiment of the present invention can remove about 9 W/cm^2 of surface area. The addition of an electric powered liquid turbine micro-pump to the liquid inlet line of the evaporator could allow the capacity of the system to be increased to above 100 W/cm^2 of surface area. This could be a feasible addition to desk top computers, work stations, mini-towers, servers and other computers where power consumption is not a critical limitation, but could not be as

attractive for laptop computers where it is desired to maximize useful battery life.

Capillary pumping is a passive surface tension effect with no need for mechanical or electrical energy inputs. A capillary-pumped two-phase thermal cycle is completely automatic and self-initiating as a consequence of a heat gain in the liquid phase refrigerant fluid in the evaporator caused by operation of the microprocessor. A particular advantage of the pure capillary-pumped two-phase thermal management apparatus of the present invention is that there is no need for pumps or other mechanical or electro-mechanical devices to circulate the working refrigerant fluid. Thus, the capillary pumped apparatus of the present invention avoids disadvantages of electro-mechanical systems such as moving parts, mechanical vibration, additional power requirements, and greater system complexity. Moreover, unlike conventional, centralized, non-redundant cooling systems wherein a general system failure due to a power loss or mechanical failure could result in the microprocessor be subject to operation without its vital heat rejection system, the apparatus of the present invention provides immunity from these power and mechanical failures. In a particularly preferred embodiment the present invention further comprises an apparatus having a multitude of small parallel connected capillary-pumped segments which provide redundancy for long-term operation in a multitude of environments.

Of particular advantage in the apparatus of the present invention is that the greater the heat generated by the microprocessor, the faster the rate of evaporation of the working

liquid phase refrigerant fluid in the evaporator and consequently the greater the rate of heat removal.

A further particular advantage of the apparatus of the present invention is that it requires no parasitic power and no electronic or mechanical controls. Since there are no moving parts, the system is inexpensive to manufacture and can operate reliably for extended periods of time with no maintenance.

In applications where increased heat removal capacity is desired, a hybrid capillary-pumped/actively-pumped configuration is possible. In a hybrid system an electric powered micro-pump can be added to the liquid inlet lines of each of the capillary pumped evaporators. The result of doing this would be a hybrid capillary-pumped/actively-pumped system that would have a heat transport capability that would be an order of magnitude greater than a simple passive capillary pumped system. However, a disadvantage of this approach would be that the pump would impose a significant parasitic power consumption on the host system. This increased power consumption would pose no major problems for desk top systems and the like that derive their power from power sources such as from a wall outlet, but the penalty in decreased battery lifetimes for portable notebook and lap top systems may be more that most users would be willing to accept. Nonetheless, the addition of a small pump to the liquid inlet of a capillary pumped two phase heat transport system an greatly increase the efficiency of the cooling system of desk top personal computer systems, business workstations and scientific supercomputers.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become better understood by reference to the following drawings, wherein:

Figure 1 is a schematic of the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 2 is a schematic diagram of a thermal management system having a capillary pumped, two-phase heat transport system.

Figure 3 is a an enlargement of an evaporator section of a capillary-pumped loop cooling apparatus.

Figure 4a is a thermodynamic diagram of a complete capillary-pumped system cycle.

Figure 4b is a profile of temperature and pressure at various duct stations in the capillary-pumped loop of Fig. 3.

Figure 5 is a cross-sectional view of a first embodiment of an evaporator capillary pump of the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 6 is a cross-section of a second embodiment of a single evaporator capillary pump of the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 7 is a cross-sectional view of the evaporator capillary pump of Fig. 6 with a linkage to a dry-out isolator.

Figure 8 is a cross-sectional side view of a dry-out isolator.

Figure 9 is an evaporator cold-plate assembly for the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 10a is a vertical cross-sectional view of another embodiment of the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 10b is a horizontal cross-sectional view of another embodiment of the capillary-pumped loop cooling apparatus for a microprocessor.

Figure 11 is a cross-sectional side view of another embodiment of a capillary evaporator of the present invention.

Figure 12 is a front cross-sectional view of the capillary evaporator of Fig. 11.

Figure 13 is a schematic diagram of a hybrid capillary-pumped/actively-pumped computer thermal management apparatus of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The foregoing aspects and many of the attendant advantages of the present invention will become more readily appreciated from the following description of a presently preferred embodiment thereof with reference to the accompanying drawings, wherein like reference characters designate like parts throughout the several views.

Referring to Fig. 1, there is shown an electronic apparatus denoted generally at 20 having a package 21 containing a heat generating electronic component 22. Electronic component 22 has a heat removal system 23 according to the present invention that utilizes a two phase fluid, not shown, as a moving substance in an active heat removal system. Suitable fluids that can be used as refrigerants have a low molecular weight, such as halogenated

alkanes examples of which include, among others: trichlorofluoromethane, dichlorodifluoromethane carbon tetrafluoride, cryofluorane and octafluorocyclobutane, of which cryofluorane is particularly useful. Distilled water can also be used. A driving force to circulate the refrigerant fluid comes from a pressure rise in a capillary structure in an evaporator. The system will only operate if the pressure rise in the capillary evaporator is at least equal to the sum of the pressure drops in the rest of the system. In certain parts of the system, two-phase flow of the working refrigerant fluid can be expected, so special pressure drop correlations must be used.

Heat removal system 23 is comprised of an evaporator 24 mounted on and in intimate physical contact with electronic component 22. Evaporator 24 is connected by a vapor conducting pipe 26 to a condenser denoted generally at 28. Condenser 28 has a plurality of coils 30 which are mounted to a cover 32 of apparatus 20. A thermally conductive radiator plate 34 is also mounted to cover 32. A liquid conducting pipe 36 connects condenser 28 back to evaporator 24 and provides a closed loop fluid communication therebetween. Mounted on radiator plate 34 are a plurality of fins 38. Fins 38 increase the surface area exposed to an ambient atmospheric heat sink 40 and thereby aid in conduction of heat from the working refrigerant fluid flowing in the closed loop system between evaporator 24 and condenser 28.

In a two-phase capillary-pumped loop heat is transported by the latent heat of vaporization of the working refrigerant fluid without the need to provide electro-mechanical pumps to circulate

the refrigerant fluid. The driving force to circulate the refrigerant fluid comes from a pressure rise in a capillary structure in evaporator 24.

As depicted in Fig. 1, evaporator 24 includes a plurality of cold plates 25 in direct physical contact with the package 21 of electronic component 22. Heat enters cold plates 25 by thermal conduction from package 21, which contains an integrated circuit that generates heat during its operation and thus comprises a heat source. Cold plates 25 are connected in parallel and each cold plate has a plurality of capillary pumps connected thereto. Heat is conducted from cold plates 25 to evaporator 24. As described hereinbelow, evaporator 24 contains a refrigerant fluid in a liquid phase. When the heat conducted to evaporator 24 provides the requisite heat of vaporization, the refrigerant fluid undergoes a phase change to a vapor phase, using the generated heat, and thus removing it. Associated with the phase change, the generated heat causes an increase in a pressure of the vapor phase refrigerant fluid relative to a pressure of the liquid phase refrigerant fluid and thus provides the driving force needed to circulate the refrigerant fluid. Capillary forces in evaporator 24 provide additional pressure required to drive the vapor phase refrigerant fluid through the loop.

The vapor phase refrigerant fluid from evaporator 24 flows through vapor pipe 26 to condenser 28 which, in the preferred embodiment, is located in a cover 32 of an electronic apparatus 20, such as a cover of a notebook computer. Condenser 28 is located under metal radiator plate 34 in cover 22 and is exposed to an

ambient atmospheric heat sink 40. Alternatively, condenser 28 can be connected to external sidewalls of the notebook computer's case. When heat is dissipated at condenser 28 to atmospheric heat sink 40, refrigerant fluid undergoes a second phase change whereby it condenses back to a liquid phase and thereby simultaneously effectuates a reduction in pressure. The liquid phase refrigerant fluid then flows back to or returns to evaporator 24 through liquid return pipe 36 to complete the cycle.

Referring to Fig. 2, in which a complete capillary-pumped loop 41 is shown, a plurality of evaporators 24 are connected by a vapor conducting pipes 26 to condenser 28 having a plurality of coils 30. Refrigerant fluid in a vapor phase flows in a direction indicated by arrow 42 from evaporators 24 to condenser 28. Liquid conducting pipe 36 connects condenser 28 back to evaporator 24 thereby completing the loop. Refrigerant fluid in a liquid phase flows in the direction of an arrow 44 from condenser 28 to evaporators 24. One or more vapor isolators 46 receive the liquid refrigerant fluid from liquid conducting pipe 36 and provide the refrigerant fluid to evaporators 24. A refrigerant fluid reservoir 48 is connected to liquid conducting pipe 36 through the one or more vapor isolators 46.

Referring to Fig. 3 in conjunction with Fig 2, a highly simplified enlargement of the two-phase heat transfer cycle of the present invention is shown. Vapor phase refrigerant fluid 50 enters condenser 28 at an entrance plenum 52 and condenses in a tank area 54 to a liquid phase refrigerant 56. Liquid phase refrigerant fluid 56 then flows in direction of arrow 44 through

liquid return pipe 36 to an inlet plenum 58 at a base 60 of a first porous medium 62 within evaporators 24. Liquid phase refrigerant fluid 56 then flows to a capillary-wick structure 64 having a pore diameter D_p. Capillary-wick structure 64 can be any of a number of low thermal conductivity fine-pored wick materials such as fine glass or mineral wool. Liquid phase refrigerant fluid 56 flows to an interface region 66 in porous medium 62 and, if sufficient heat energy is added from outside evaporator 24, moves across a high radius of curvature menisci 68 present at a liquid/vapor interface 70, where it undergoes a phase change and becomes vapor phase refrigerant fluid 50. After crossing menisci 68, vapor phase refrigerant fluid 50 enters an outlet section 72 as a high pressure saturated vapor. Vapor phase refrigerant fluid 50 becomes superheated as it flows to an end 74 of porous medium 62, from which vapor phase refrigerant fluid 50 then flows in the direction of arrow 42 through vapor pipe 26 towards condenser 28 to complete the cycle.

Referring to Fig. 4a, a thermodynamic diagram of the complete capillary-pumped system cycle, and Fig. 4b, a diagrammatic representation of the refrigerant cycle that is keyed to the thermodynamic diagram of Fig. 4a., there is shown the curve for cryofluorane as the refrigerant fluid. The fluid pressure is shown on the ordinate or y-axis of Fig. 4a and the fluid temperature is shown on the abscissa or x-axis of Fig. 4a. P_{LB1} represents the pressure on the liquid side of liquid/vapor interface 68 shown in Fig. 3 and P_{V1} represents the pressure on the vapor side of interface 68. P_{VE1} represents the pressure of vapor phase

refrigerant fluid 50 at exit end 74 of wick 64, and P_U and P_D are respectively representative of the pressures upstream and downstream from condenser 28. The heat of vaporization is depicted as the curve from point P_{L1} to point P_{V1}, and the heat of condensation is depicted as the curve from point P_U to Point P_D.

Referring to Fig. 4b, a plot of the distance along the physical cycle versus the refrigerant fluid temperature is depicted with the solid line and a plot of the refrigerant fluid pressure is depicted with the dashed line. The positions along the distance are provided for the various relative positions 52, 54, 58, 60, 66 and 74 of loop 41 denoted in Fig. 3.

Accordingly, and with reference now to Fig. 5, in accordance with a first preferred embodiment of the present invention evaporator 24 comprises a capillary pump 75 which comprises a plurality of liquid supply pipes 76. Each liquid supply pipe 76 is connected at one end to liquid return pipe 36, as shown in Figs. 1-2, and is connected longitudinally to corresponding one ends of a plurality of narrow capillary channels 78, each of which is preferably of generally less than 1mm. Capillary channels 78, which carry liquid phase refrigerant fluid 56 are connected at the other end to a plurality of v-shaped grooves 80. Capillary grooves 80 in the preferred embodiment are generally machined at greater than 100 per inch. Capillary grooves 80 are disposed on all inside surfaces 82 of closed evaporator enclosure 84. Throughout a central portion of enclosure 84 is a vapor flow channel 90 defined by walls 92 of evaporator enclosure 84. Vapor flow channel 90 is connected to vapor conducting pipe 26 (not shown in Fig. 5). As can be seen in Fig. 5, evaporator 24 is mounted directly to the

outside of package 21 of electronic component 22, which in Fig. 5 is microprocessor 86.

In evaporator 24 liquid phase refrigerant fluid 56 is received from liquid return pipe 36 and flows into liquid supply pipes 76 and then through capillary channels 78 to grooves 80 across inside surfaces 82 of capillary pump 75. Heat generated by microprocessor heat source 86 is conducted through evaporator enclosure 84 and absorbed by liquid phase refrigerant fluid 56 heating liquid phase refrigerant fluid 56 to its heat of vaporization which then thereby evaporates - undergoing a phase change becoming vapor phase refrigerant fluid 50 which is at a significantly higher pressure than liquid phase refrigerant fluid 56. Evaporating liquid phase refrigerant fluid 50 passes from grooves 80 across a capillary interface (not shown) becoming vapor phase refrigerant fluid 50. Vapor phase refrigerant fluid 50 enters vapor flow channel 90 and then flows to vapor conducting pipe 26. The increase in pressure causes both liquid phase refrigerant fluid 56 and vapor phase refrigerant fluid 50 to flow throughout the entire loop 41.

Liquid supply pipes 76 are drilled out of a block of low thermal conductivity material 94 such as Teflon, which insulates liquid refrigerant fluid 56 in supply pipes 76 and keeps it from boiling with a consequent destruction of the capillary interface (not shown).

Referring now to Figs. 6-7, in accordance with a second preferred embodiment of the present invention evaporator 24 is comprised of a plurality of high performance capillary pumps, one of which is shown as capillary pump 96. Capillary pump 96 is an elongated cylinder having an outer annular wall or portion 98; an inner channel 100 defined by an inner concentric wall 102, and a

concentric annular porous wick structure 104 located therebetween. Outer annular portion 98 has a plurality of axially aligned vapor flow channels 106 distributed around the inner surface 108 of wall 98. Wick 104 has a plurality of outer cylindrical surfaces 110 that are opposite corresponding ones of channels 106 and define the inner surface thereof. Wick 104 has a corresponding plurality of inner cylindrical surfaces 112 on an opposite side thereof. Inner cylindrical surfaces 112 define inner concentric wall 102 which defines liquid supply pipe 100. Liquid phase refrigerant fluid 56 enters capillary pump 96 through liquid supply pipe 100 from which it enters cylindrical wick structure 104 across inner cylindrical surfaces 112. Heat is conducted from electronic component 22, as shown in Fig. 1, through wall 98 and absorbed by liquid phase refrigerant fluid 56 in wick 104. When liquid phase refrigerant fluid 56 reaches it heat of vaporization it evaporates thereby undergoing a phase change to vapor phase refrigerant fluid 50. As the molecules of liquid phase refrigerant fluid 56 pass a liquid/vapor interface (not shown) and thereby become vapor phase refrigerant fluid 50, with added heat they undergo a pressure increase. The pressure increase causes vapor phase refrigerant fluid 50 to pass from porous wick structure 104 across the plurality of outer cylindrical surfaces 110 and enter the plurality of vapor flow channels 106 which are connected to vapor conducting pipe 26.

Capillary pump 96 further comprises three longitudinally connected portions 114, 116, and 118. First portion 114 is generally cylindrical and has a first interior diameter 120. Second portion 116 is generally a frustrum of a conical section and has a second interior diameter 122 generally greater than first

interior diameter 120, and a third interior diameter 124 generally greater than second interior diameter 122. Third portion 118 is connected between portions 114 and 116. Third interior diameter 124 is also common to portion 118 and is approximately the same as an outer diameter of porous wick structure 104. Third portion 118 also has a fourth interior diameter 126 defined by a diameter of inner channel 100 and which is greater than first interior diameter 120. An inlet end 128 of first portion 114 is connected to liquid inlet pipe 130 at a first end 132 thereof. An outlet end 134 of first portion 114 is connected to an inlet end 136 of third portion 118. An outlet end 138 of third portion 118 is connected to an inlet end 140 of second portion 116. An outlet end 142 of second portion 116 is connected to vapor conducting pipe 26. A second end 144 of liquid inlet pipe 130 is connected to vapor isolator 46.

Capillary pump 96 has a first inactive zone 146 defined longitudinally as extending from vapor isolator 46 to a discharge port 148 interior to capillary pump 96 where first interior diameter 120 is transitioned to fourth interior diameter 126. Port 148 defines a beginning of inner channel 100. Liquid phase refrigerant fluid is supplied through first inactive zone 146 to port 148. Capillary pump 96 has a second inactive zone 150 defined longitudinally from an end 152 of cylindrical wick structure 104 opposite port 148 and includes second portion 116 and a portion of vapor conducting pipe 26. Connected between first inactive zone 146 and second inactive zone 150, capillary pump 96 has an active zone 154. Third portion 118 comprises active zone 154 and has cylindrical wick structure 104 disposed therein. End 152 of cylindrical wick structure 104 has a plug 156 which defines an end of inner channel 100.

In active zone 134 liquid phase refrigerant fluid 56 traveling in direction 44 is received through port 148 into inner channel 100. Liquid phase refrigerant fluid 56 fills inner channel 100 and flows to inner cylindrical surfaces 112 and enters cylindrical wick structure 104. Heat from electrical component 22 (shown in Fig. 1) is conducted through outer annular wall 98 and is absorbed by liquid phase refrigerant fluid 56. When liquid phase refrigerant fluid 56 absorbs sufficient heat to reach its heat of vaporization the liquid phase refrigerant fluid 56 in wick 104 evaporates thereby undergoing a phase change to vapor phase refrigerant fluid 50. As the molecules of liquid phase refrigerant fluid 56 pass a liquid/vapor interface and thereby become vapor phase refrigerant fluid 50, they also undergo a pressure increase. The pressure increase causes vapor phase refrigerant fluid 50 to pass from porous wick structure 104 across outer cylindrical surfaces 110 from and to enter axial vapor flow channels 106. Vapor phase refrigerant fluid 50 travels in direction 42 through channels 106 and enters vapor conducting pipe 26 to be provided to the condenser..

Referring now to Fig. 8, an isolator assembly 46 is depicted. Isolator assembly 46 prevents vapor phase refrigerant fluid 50 from back flowing into liquid return pipe 36, shown in Figs. 1-2, or liquid inlet pipe 130, as shown in Fig. 7. Isolator assembly 46 is connected to liquid return pipe 36, as shown in Figs. 1-2. Back flow could occur if any of the plurality of capillary pumps 75 and 96, dried out. If a dry out occurs, the back flow of vapor phase refrigerant fluid 50 could cut off flow of liquid phase refrigerant 56 to others of the plurality of capillary pumps 75 and 96.

Isolator 46 has an inlet end 158 and an outlet end 160. Multiple isolators 46 can be connected serially such that outlet end 158 of an (n-1)-th serially connected isolator 46 can be connected to inlet end 160 of an n-th serially connected isolator 46. Outlet end 160 of isolator 46 in a singular installation or a last isolator 46 in an assembly of serially connected isolators 46 can be connected to a reservoir 48 as shown in Fig. 2, or can be capped. Inlet end 158 of a first isolator 46 is connected to liquid return pipe 36, such as shown in Fig. 2.

Isolator 46 comprises a manifold 162 having an inner surface 164 and an outer surface 166. A plurality of capillary pump ports 168 are disposed axially along outer surface 166 and provide fluid communication through manifold 162 with capillary pumps 75 and 96 by connector pipes such as liquid inlet pipe 130 shown in Fig. 7. Liquid phase refrigerant fluid 56 is provided to isolator 46 through inlet 170 in inlet end 158. When serially connected, a portion of liquid phase refrigerant fluid 56 flows through the (n-1)-th isolator 46, exits at outlet 172 and enters inlet 170 of the n-th serially connected isolator 46.

Disposed axially within manifold 140 is a porous cylindrical wick structure 174 similar to wick structure 104 shown in Figs. 6-7. Cylindrical wick structure 174 has an outer surface 176 and an inner surface 178. Inner wick surface 178 defines a longitudinal liquid flow pipe 180 extending the length of isolator 46. Outer wick surface 176 extends longitudinally in close proximity with inner surface 164. Between inner surface 164 and outer wick surface 176 is a liquid flow annulus 182. In the event one of the plurality of capillary pumps 75 and 96 dries out, capillary forces in wick structure 174 in conjunction with liquid flow annulus 182

prevent vapor phase refrigerant fluid 50 from back flowing from the dried out capillary pump 75 and 96 and from entering another of the plurality of capillary pumps 75 and 96.

Referring now to Fig. 9, a complete evaporator 24 is shown. Evaporator 24 has a plurality of capillary pumps such as the four capillary pumps 96 which are shown. The plurality of capillary pumps 96 are connected in parallel to isolator 46 by liquid inlet pipes 130 connected to respective inlet ends 128 of first portions 114 of each capillary pump 96, such as shown in Fig. 7. Outlet ends 142 of each capillary pump 96 are connected to vapor conductive pipe 26. Evaporator 24 has a thermally conducting evaporator cold plate 184. Cold plate 184 is connected in direct physical or intimate thermal contact with heat generating electrical component 22, shown only in Fig. 1, such as microprocessor 86 shown in Fig. 5. Cold plate 184 receives heat generated by component 22 and conducts the heat to capillary pumps 96. Evaporator 24 can remove more than an order of magnitude more heat per unit surface area than a similarly sized single phase heat transport system such as a passive heat sink.

Referring now to Figs. 10a-10b, a further specific embodiment of the apparatus of the present invention is shown. An integrated cooling apparatus 200 having both an evaporation zone 202 and a condensing zone 204 is shown connected to a microprocessor 86. Integrated cooling apparatus 200 comprises a generally cylindrical enclosure 206 having a porous wick structure 208 lining an inner surface thereof. Liquid phase refrigerant fluid 56 flows in direction 210 through wick 208 to a bottom 212 of enclosure 206 where it enters evaporation zone 202. Liquid phase refrigerant fluid 56 absorbs heat conducted from microprocessor 86 until it

reaches it heat of vaporization whereupon it undergoes a phase change to vapor phase refrigerant fluid 50. Vapor phase refrigerant fluid 50 travels in a direction 214 towards condensing zone 204. When vapor phase refrigerant fluid 56 comes in contact with wick 208 along a top 216 and sides 218 of enclosure 206 it condenses to liquid phase refrigerant fluid 56 and thereby transfers its heat to cylindrical enclosure 206 which conducts and radiates the heat through fins 220 to atmospheric heat sink 222.

With reference to Figs. 11-12, a particularly preferred embodiment of an evaporator 230 of the present invention comprises a capillary pump 232 which can be joined in intimate contact with a heat generating electronic component 234. Capillary pump 232 has a plurality of liquid supply pipes or channels 236. Each liquid supply pipe or channel 236 is connected at one.end 238 to liquid return pipe 36. Liquid phase refrigerant 56 from liquid return pipe 36 flows in a direction indicated by arrow 239 and enters capillary pump 232 through liquid supply pipes 236 from which it then enters porous wick structure 240 across lower portions 242 of wick 240. Heat from electronic component 234 is conducted through wall 244, which is preferably made of a high thermal conductivity material, and is absorbed by liquid phase refrigerant fluid 56 in wick 240. Bottom portion 246 of capillary pump 232 is preferably made of a very low thermal conductivity material. When liquid phase refrigerant fluid 56 reaches its heat of vaporization, it evaporates thereby undergoing a phase change to vapor phase refrigerant fluid 50. As the molecules of liquid phase refrigerant fluid 56 pass through a liquid/vapor interface (not shown) and thereby become vapor phase refrigerant fluid 50, with added heat they undergo a pressure increase. The pressure increase causes

vapor phase refrigerant fluid 50 to pass from wick structure 240 across top planar surfaces 248 of wick 240 and enter vapor flow channels 250, which are connected to vapor conducting pipe 26, through which vapor phase refrigerant 50 exits evaporator 232 flowing in direction 251.

Referring now to Fig. 13, a schematic of a hybrid capillary pumped/actively pumped system is shown. In the hybrid system shown in Fig. 13 liquid pump 280 is connected serially in liquid return line 282 between condenser 284 and capillary evaporator 286. A vapor pump (not shown) can also be connected serially in vapor line 288 between capillary evaporator 286 and condenser 284.

Although the preferred embodiments of the present invention have been disclosed for illustrative purposes, those skilled in the art will appreciate that various modifications, additions and substitutions are possible without departing from the scope and spirit of the invention as disclosed in the accompanying claims.

I claim:

CLAIMS

1. A capillary-pumped two-phase thermal management system for transporting heat from a heat source to a heat sink, said thermal management system comprising:

a refrigerant fluid having a vapor phase and a liquid phase;

an evaporator in thermal heat conducting communication with said heat source, said evaporator receiving said refrigerant fluid in a liquid phase and utilizing heat from said heat source for converting said liquid phase refrigerant fluid to said vapor phase refrigerant fluid, said evaporator comprising a plurality of capillary pumps, each of said plurality of capillary pumps having a liquid inlet and a vapor outlet;

a condenser receiving said vapor phase refrigerant fluid and discharging heat therefrom to a heat sink resulting in a conversion of said vapor phase refrigerant fluid to said liquid phase refrigerant fluid, said condenser having a vapor inlet and a liquid outlet, said vapor inlet being in fluid communication with each of said vapor outlets of said plurality of capillary pumps;

a vapor isolator which can isolate a capillary pump from other capillary pumps, said vapor isolator having an inlet and a plurality of outlets wherein said inlet of said vapor isolator is in fluid communication with said liquid outlet of said condenser, and at least one of said plurality of outlets of said vapor isolator is in fluid communication with a corresponding one of a liquid inlet of said plurality of capillary pumps.

2. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said evaporator further comprises a cold

plate thermally connected to said heat source and thermally connected to one of said plurality of capillary pumps.

3. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said heat source is an integrated circuit and wherein said evaporator is in direct physical contact with said integrated circuit heat source.

4. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said condenser is in thermal communication with a heat sink.

5. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said evaporator further comprises:

a plurality of liquid supply pipes;

a plurality of capillary channels in fluid communication with corresponding ones of said plurality of liquid supply pipes;

an evaporator wall having a first inner surface with a plurality of capillary grooves disposed thereon, said plurality of capillary grooves being in fluid communication with corresponding ones of said plurality of capillary channels; and

a vapor flow channel defined by said first inner surface of said evaporator wall, said vapor flow channel being in fluid communication with said plurality of capillary grooves.

6. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said evaporator further comprises:

a cylindrical outer wall having a second inner surface;

a plurality of axial grooves formed on said second inner surface of said cylindrical outer wall;

a cylindrical first porous wick having an inner radial surface and a first outer radial surface disposed within said cylindrical outer wall, and said inner radial surface defining a second outer radial surface of a liquid supply pipe.

7. The capillary-pumped two-phase thermal management system as claimed in claim 6 wherein said cylindrical first porous wick is coaxially disposed in said cylindrical outer wall with said first outer radial surface disposed adjacent said second inner surface.

8. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein each of said plurality of capillary pumps further comprises:

a centrally located active zone have a first end and a second end;

a first inactive zone disposed adjacent said first end near said liquid inlet;

a second inactive zone disposed adjacent said second end near said vapor outlet;

a tubing having a length and a closed perimeter wall having a third inner surface, wherein said length is disposed axially and extends from at least a part of said first inactive zone to at least a part of said second inactive zone;

a plurality of axial grooves disposed on said third inner surface, said plurality of axial grooves extending from at least a part of said first inactive zone to at least a part of said second inactive zone; and

a first porous wick having a first side and a second side disposed within said tubing.

9. The capillary-pumped two-phase thermal management system as claimed in claim 8 wherein said plurality of axial grooves further comprises a plurality of vapor flow channels.

10. The capillary-pumped two-phase thermal management system as claimed in claim 9 wherein said first side of said first porous wick is in fluid communication with said liquid inlet and said second side of said first porous wick is in fluid communication with said plurality of vapor flow channels.

11. The capillary-pumped two-phase thermal management system as claimed in claim 9 wherein said plurality of vapor flow channels is in fluid communication with said vapor outlet.

12. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said vapor isolator further comprises:

a manifold having a closed perimeter wall having a length and a fourth inner surface, a first end, a second end, a second liquid inlet, a second liquid outlet, and a plurality of capillary pump return outlets;

a second porous wick having a third side defining a flow pipe and a fourth side, said second porous wick being disposed internal to said manifold adjacent said fourth inner surface and between said first end and said second end; and

a liquid flow annulus between said fourth side of said second porous wick and said fourth inner surface of said manifold;

wherein said second liquid inlet and said second liquid outlet are in fluid communication with said flow pipe; and

wherein said plurality of capillary pump return outlets are in fluid communication with said liquid flow annulus.

13. The capillary-pumped two-phase thermal management system as claimed in claim 1 further comprising a reservoir in fluid communication with said vapor isolator.

14. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said plurality of capillary pumps are connected in parallel.

15. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said refrigerant fluid is selected from the group consisting of the low molecular weight halogenated alkanes examples of which include, among others: trichlorofluoromethane, dichlorodifluoromethane carbon tetrafluoride, cryofluorane and octafluorocyclobutane.

16. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said refrigerant fluid is water.

17. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said heat source is an integrated circuit mounted on a circuit board; and further comprising:

a housing, said housing comprised of a base in which said circuit board is mounted; and

a cover; and

wherein said condenser include a plurality of loops mounted to said cover.

18. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said heat source is an integrated circuit comprised of an outer package and an internal electronic heat generating circuitry, and wherein said evaporator is mounted on said outer package.

19. The capillary-pumped two-phase thermal management system as claimed in claim 1 wherein said evaporator further comprises:

a high thermal-conductivity first housing;

a low thermal-conductivity second housing connected to said first housing, said first and second housing forming a closed chamber therebetween;

a porous wick disposed in said chamber between said first housing and said second housing, said wick having a first surface and a second surface;

at least one vapor flow channel in said closed chamber formed in said first housing adjacent said first surface of said wick and being in fluid communication with said wick through said first surface thereof;

at least one liquid supply pipe in said closed chamber formed in said wick near said second housing and being in fluid communication with said wick through said second surface thereof;

wherein said at least one vapor flow channel is in fluid communication with said vapor outlet; and

said at least one liquid supply pipe is in fluid communication with said liquid inlet.

20. The capillary-pumped two-phase thermal management system as claimed in claim 1 further comprising a liquid micro-pump serially connected between said condenser and said evaporator.

21. The capillary-pumped two-phase thermal management system as claimed in claim 1 further comprising a vapor micro-pump serially connected between said evaporator and said condenser.

22. A capillary-pumped two-phase thermal management system having an evaporator capillary pump, said evaporator capillary pump comprising:

a plurality of liquid supply pipes;

a plurality of capillary channels in fluid communication with said plurality of liquid supply pipes;

an evaporator wall having a first inner surface having a plurality of capillary grooves disposed thereon, said plurality of capillary grooves being in fluid communication with said plurality of capillary channels;

a vapor flow channel defined by said first inner surface of said evaporator wall and adjacent thereto, said vapor flow channel being in fluid communication with said plurality of capillary grooves;

wherein said vapor flow channel is in fluid communication with a vapor outlet; and

said plurality of liquid supply pipes is in fluid communication with a liquid inlet.

23. A capillary-pumped two-phase thermal management system having an evaporator capillary pump, said evaporator capillary pump comprising:

a high thermal-conductivity first housing;

a low thermal-conductivity second housing connected to said first housing, said first and second housing forming a closed chamber therebetween;

a porous wick disposed in said chamber between said first housing and said second housing, said wick having a first surface adjacent said first housing and a second surface adjacent said second housing;

at least one vapor flow channel in said closed chamber formed in said first housing adjacent said first surface of said wick and being in fluid communication with said wick through said first surface thereof;

at least one liquid supply pipe in said closed chamber formed in said wick near said second housing and being in fluid communication with said wick through said second surface thereof;

wherein said at least one vapor flow channel is in fluid communication with a vapor outlet; and

said at least one liquid supply pipe is in fluid communication with a liquid inlet.

24. A capillary-pumped two-phase thermal management system comprising, in combination:

a heat source comprising an integrated circuit electronic component;

an evaporator having a fluid inlet and fluid outlet in direct physical contact with said electronic component;

a condenser having a fluid inlet and a fluid outlet in a closed loop fluid communication with said evaporator;

a two-phase refrigerant fluid flowing in said evaporator and said condenser;

wherein said inlet of said condenser is in fluid communication with said outlet of said evaporator and said outlet of said condenser is in fluid communication with said inlet of said evaporator.

25. The capillary-pumped two-phase thermal management system as claimed in claim 24 wherein said condenser further comprises fins.

26. The capillary-pumped two-phase thermal management system as claimed in claim 24 wherein said electronic component is a microprocessor.

27. The capillary-pumped two-phase thermal management system as claimed in claim 24 further comprising an electro-mechanical pump connected serially in said closed loop.

28. A method of removing heat from an integrated circuit comprising the steps of:

initially passing a liquid phase of a fluid that has a vapor phase and a heat of vaporization such that the heat necessary to change the liquid phase to the vapor phase can be supplied by the integrated circuit through an evaporator in direct thermal communication with said integrated circuit, wherein said evaporator comprises a plurality of capillary pumps each having a first porous wick, a liquid inlet and a vapor outlet;

providing heat from said integrated circuit to said evaporator thereby evaporating said liquid phase fluid in said evaporator and thereby providing said vapor phase fluid and thereby increasing a pressure thereof;

providing said vapor phase fluid to a condenser in fluid communication with each of said plurality of capillary pumps by a pressure provided by vaporization of said liquid phase refrigerant fluid;

providing heat from said vapor phase fluid to said condenser thereby condensing said vapor phase fluid in said condenser and thereby providing said liquid phase fluid;

providing said heat from said condenser to a heat sink;

providing said liquid phase fluid from said condenser to a vapor isolator which comprises a second porous wick and a flow annulus wherein a flow of fluid to each of said plurality of capillary pumps can be isolated from others of said plurality of capillary pumps;

providing said refrigerant fluid in a liquid phase back to said plurality of capillary pumps thereby completing a cycle.

29. The method as claimed in claim 28 further comprising the step of pumping said liquid phase refrigerant fluid by a mechanical pump.

30. The method as claimed in claim 28 further comprising the step of pumping said vapor phase refrigerant fluid by a mechanical pump.

31. An evaporator for a capillary-pumped two-phase thermal management system comprising:

a plurality of liquid supply pipes;

a plurality of capillary channels in fluid communication with corresponding ones of said plurality of liquid supply pipes;

an evaporator wall having a first inner surface with a plurality of capillary grooves disposed thereon, said plurality of capillary grooves being in fluid communication with corresponding ones of said plurality of capillary channels; and

a vapor flow channel defined by said first inner surface of said evaporator wall, said vapor flow channel being in fluid communication with said plurality of capillary grooves.

32. The evaporator as claimed in claim 31 further comprising a cold plate thermally connected to a heat source and to a capillary pump.

33. An evaporator for a capillary-pumped two-phase thermal management system comprising:

a cylindrical outer wall having a second inner surface;

a plurality of axial grooves formed on said second inner

surface of said cylindrical outer wall;

a cylindrical first porous wick having an inner radial surface and a first outer radial surface disposed within said cylindrical outer wall, and said inner radial surface defining a second outer radial surface of a liquid supply pipe.

34. The evaporator as claimed in claim 33 further comprising a cold plate thermally connected to a heat source and to a capillary pump.

35. The evaporator as claimed in claim 33 wherein said cylindrical first porous wick is coaxially disposed in said cylindrical outer wall with said first outer radial surface disposed adjacent said second inner surface.

36. A capillary pump for a two-phase thermal management system comprising:

a centrally located active zone have a first end and a second end;

a first inactive zone disposed adjacent said first end near a liquid inlet;

a second inactive zone disposed adjacent said second end near a vapor outlet;

a tubing having a length and a closed perimeter wall having a third inner surface, wherein said length is disposed axially and

extends from at least a part of said first inactive zone to at least a part of said second inactive zone;

a plurality of axial grooves disposed on said third inner surface, said plurality of axial grooves extending from at least a part of said first inactive zone to at least a part of said second inactive zone; and

a first porous wick having a first side and a second side disposed within said tubing.

37. The capillary pump for a two-phase thermal management system as claimed in claim 36 wherein said plurality of axial grooves further comprises a plurality of vapor flow channels.

38. The capillary pump for a two-phase thermal management system as claimed in claim 37 wherein said first side of said first porous wick is in fluid communication with said liquid inlet and said second side of said first porous wick is in fluid communication with said plurality of vapor flow channels.

39. The capillary pump for a two-phase thermal management system as claimed in claim 37 wherein said plurality of vapor flow channels is in fluid communication with said vapor outlet.

40. An evaporator for a capillary-pumped two-phase thermal management system comprising:

a high thermal-conductivity first housing;

a low thermal-conductivity second housing connected to said first housing, said first and second housing forming a closed chamber therebetween;

a porous wick disposed in said chamber between said first housing and said second housing, said wick having a first surface and a second surface;

at least one vapor flow channel in said closed chamber formed in said first housing adjacent said first surface of said wick and being in fluid communication with said wick through said first surface thereof;

at least one liquid supply pipe in said closed chamber formed in said wick near said second housing and being in fluid communication with said wick through said second surface thereof;

wherein said at least one vapor flow channel is in fluid communication with a vapor outlet; and

said at least one liquid supply pipe is in fluid communication with a liquid inlet.

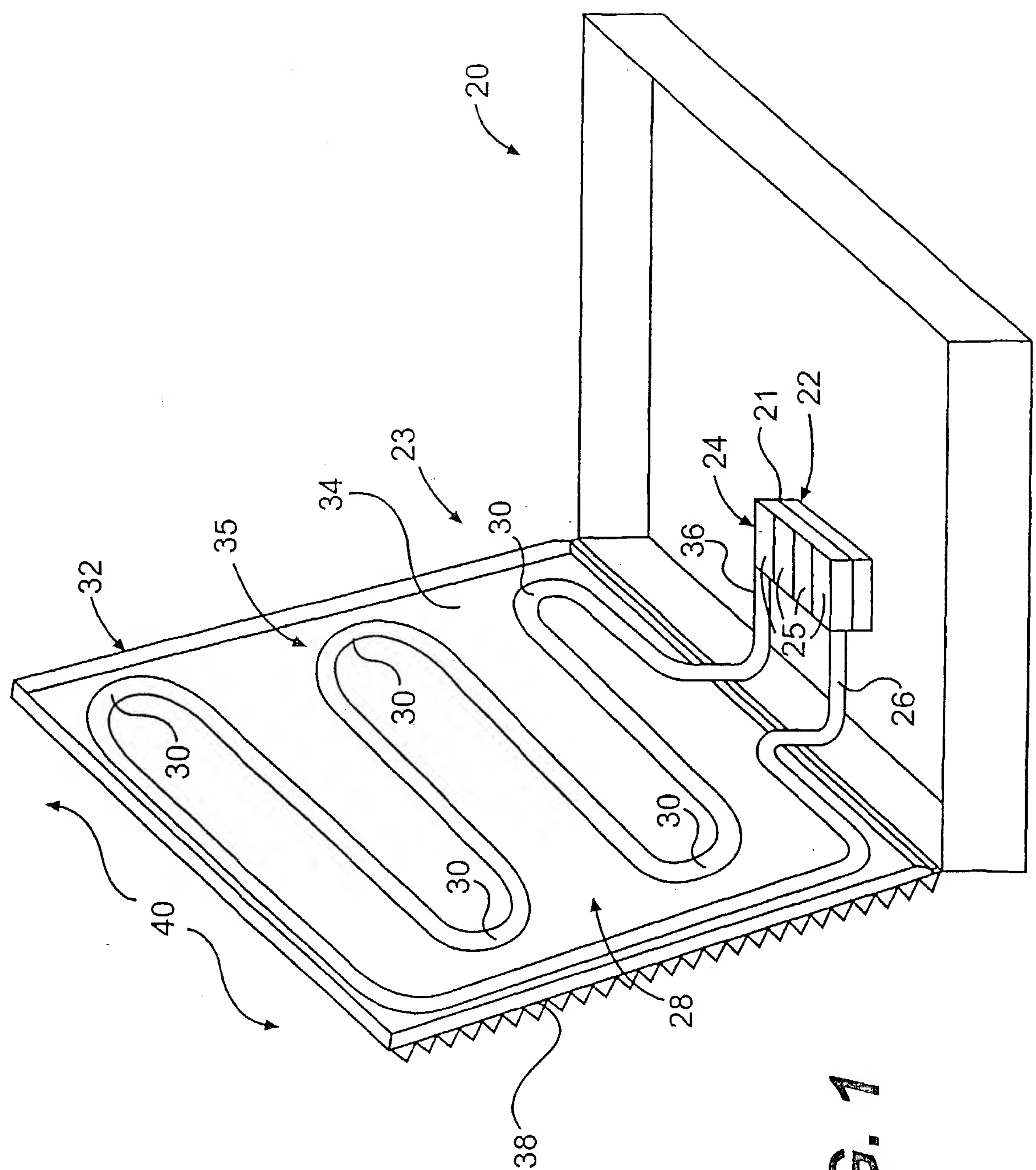


FIG. 1

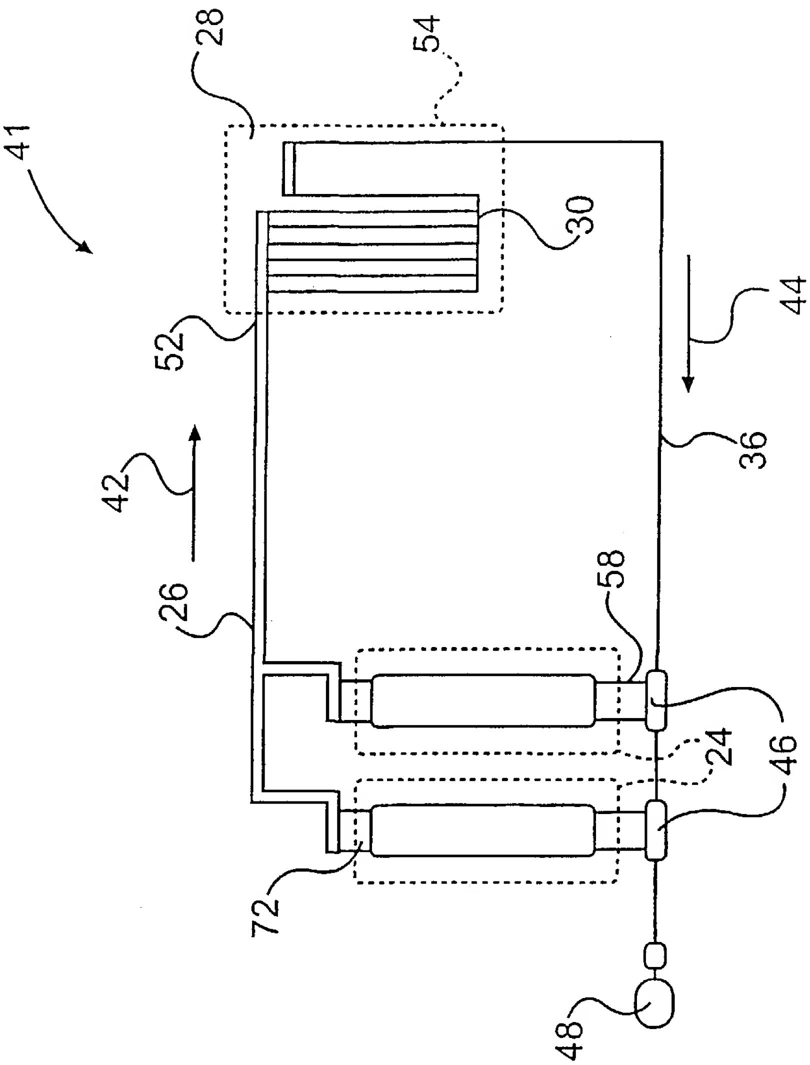


FIG. 2

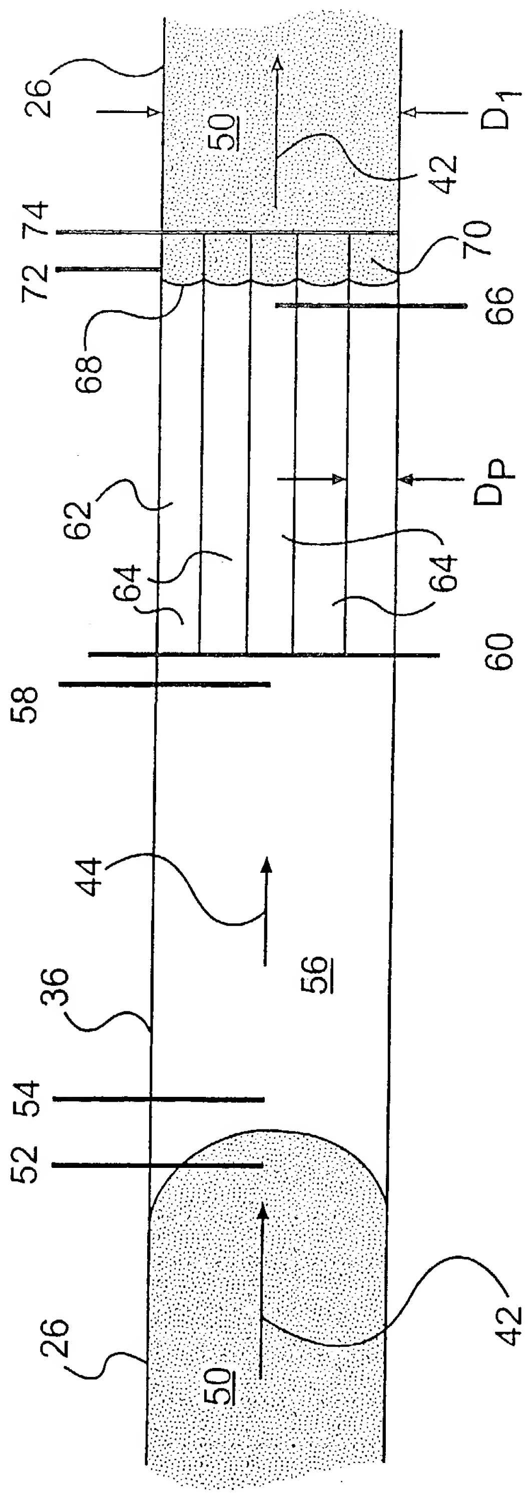
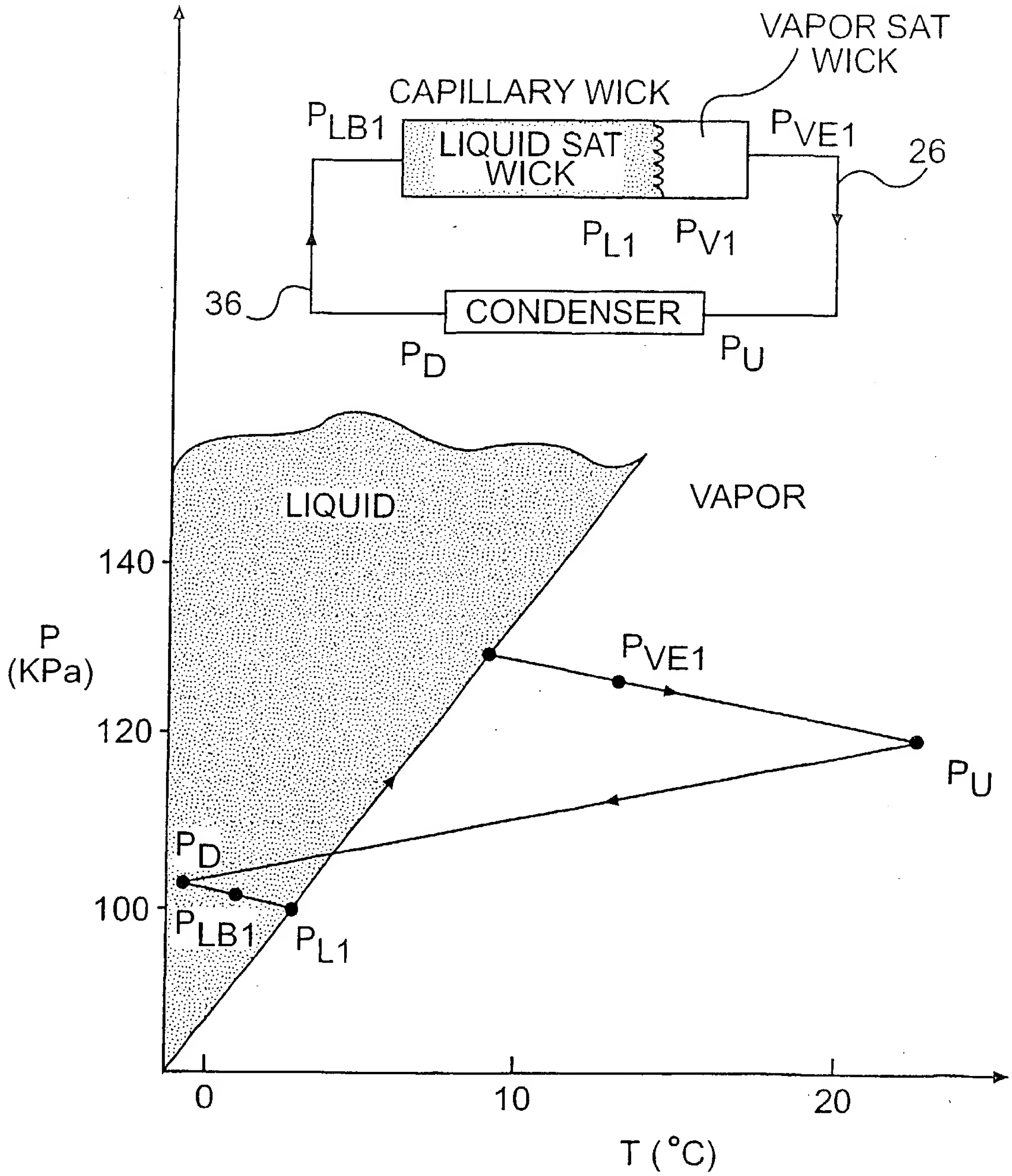


FIG. 3


VAPOR SAT WICK
CAPILLARY WICK
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LIQUID SAT WICK
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P_{L1}
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P_D
P_U
LIQUID
VAPOR
140
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P_U
P_D
P_{LB1}
P_{L1}
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FIG. 4A

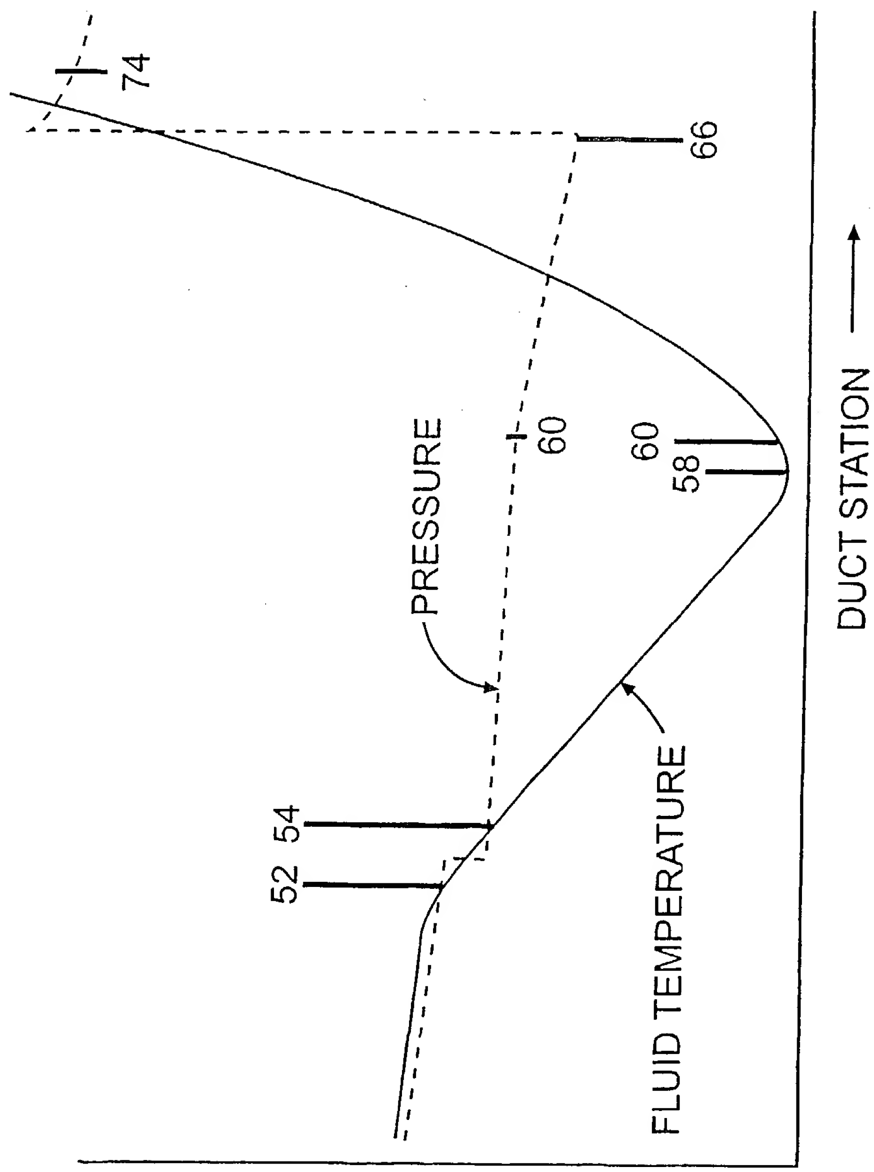

FIG. 4B

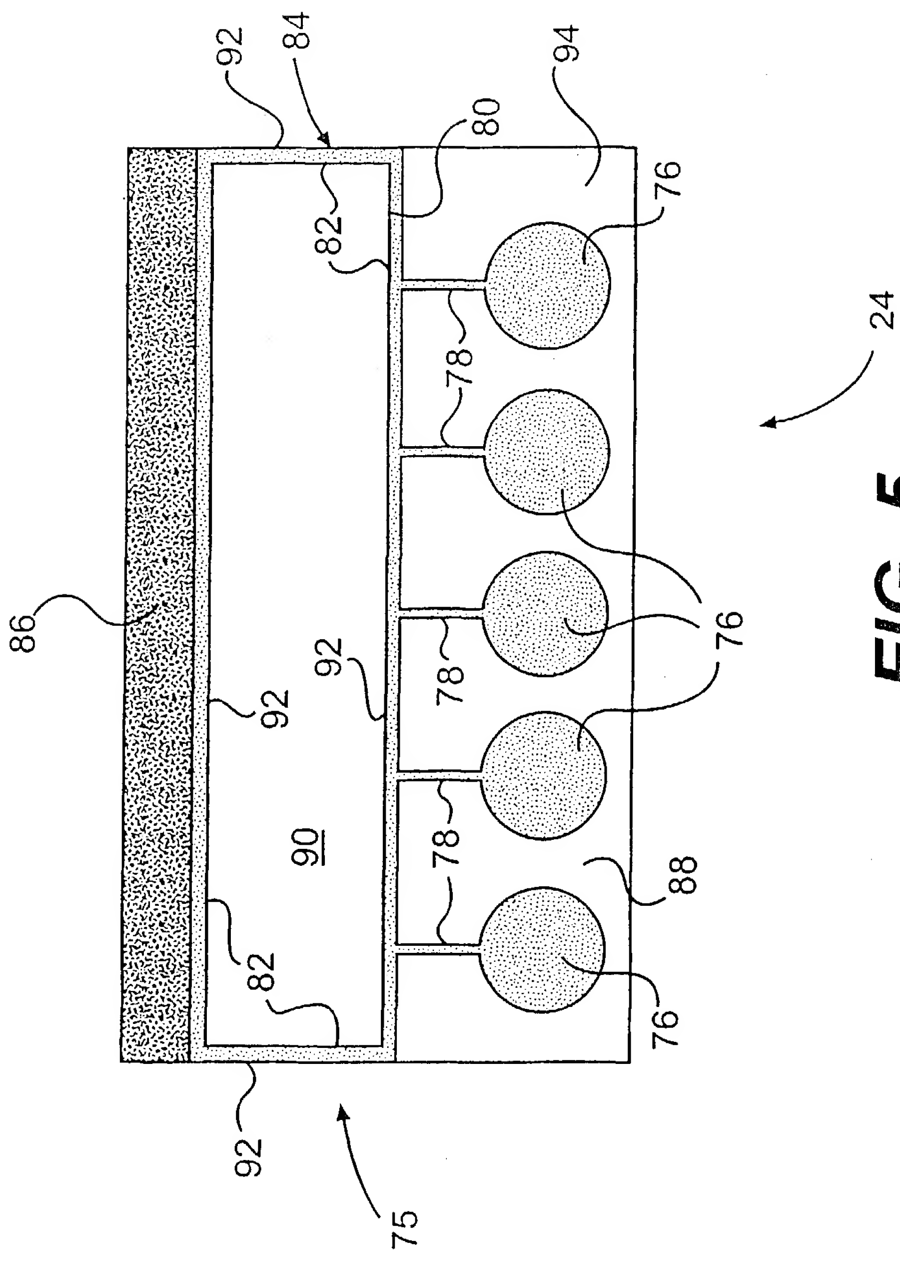

FIG. 5

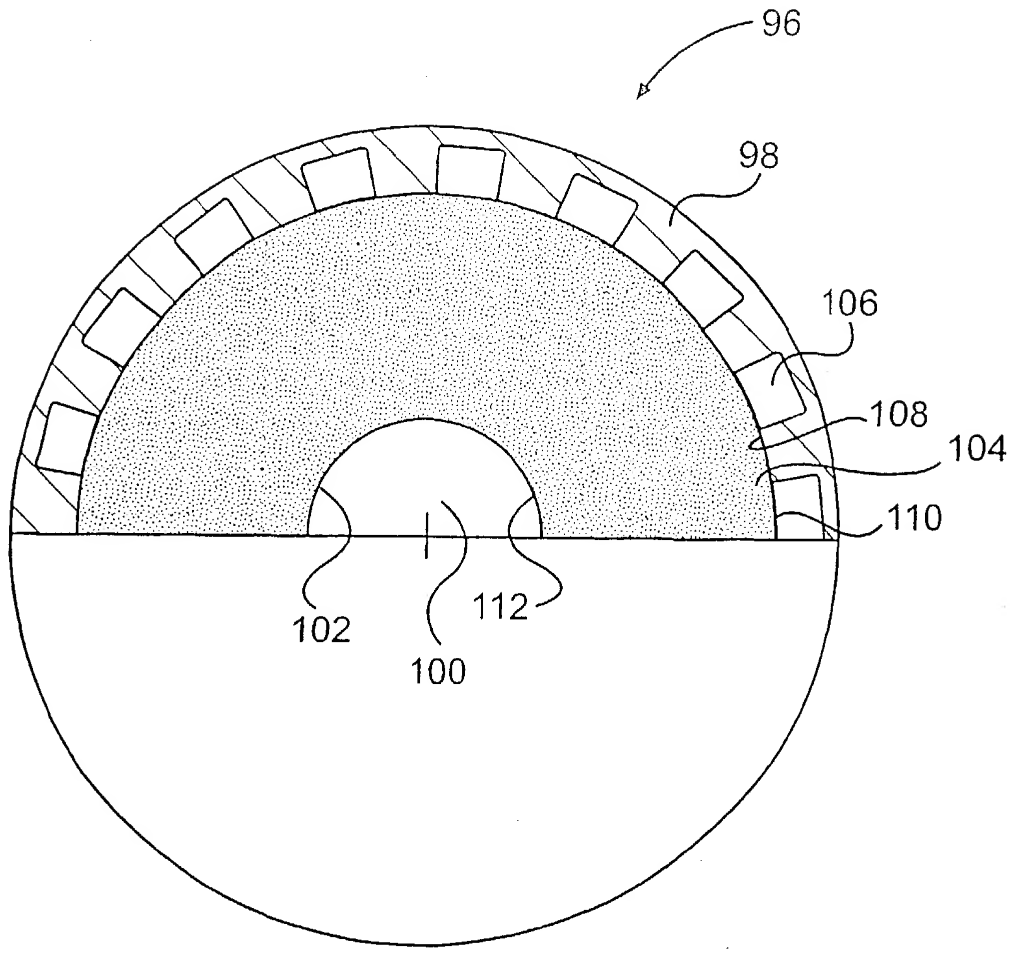

FIG. 6

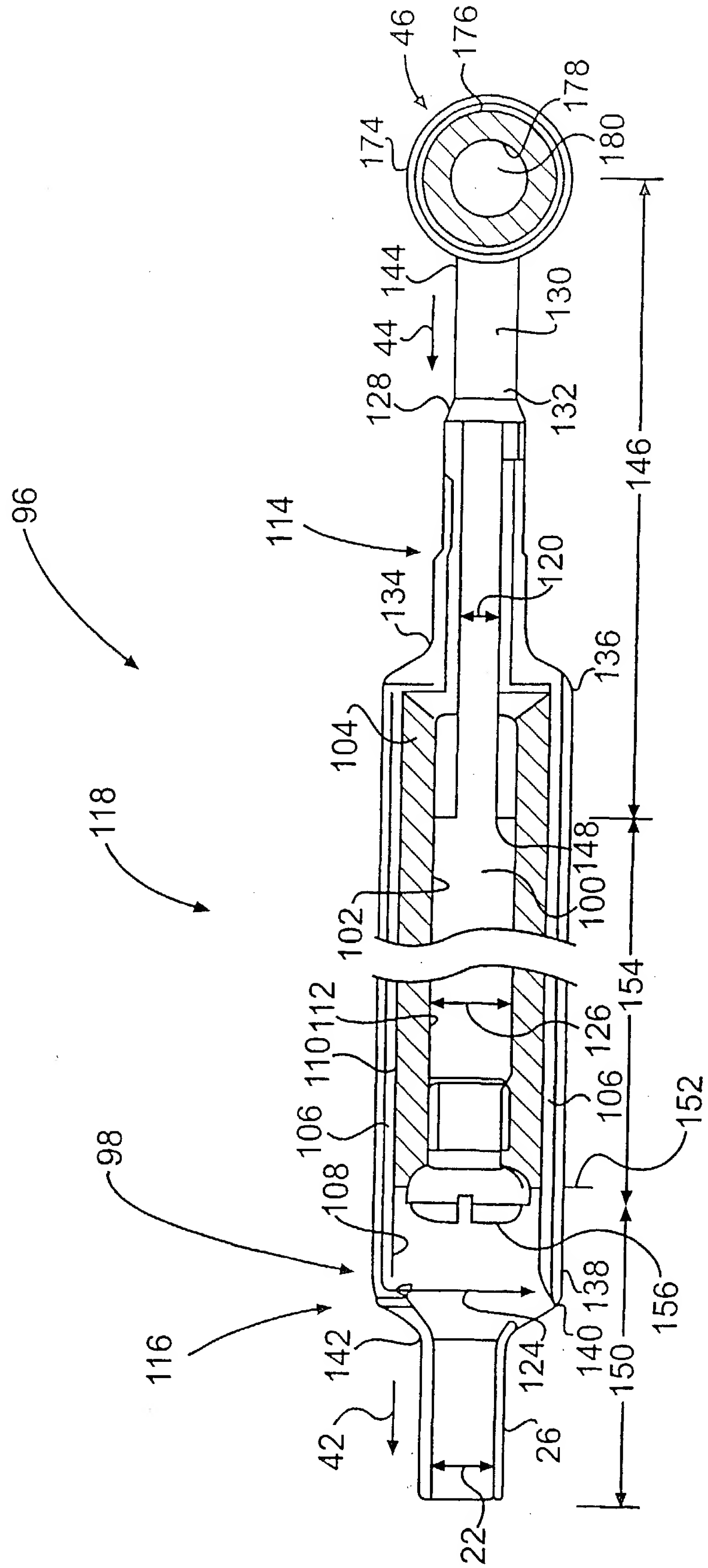
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FIG. 7

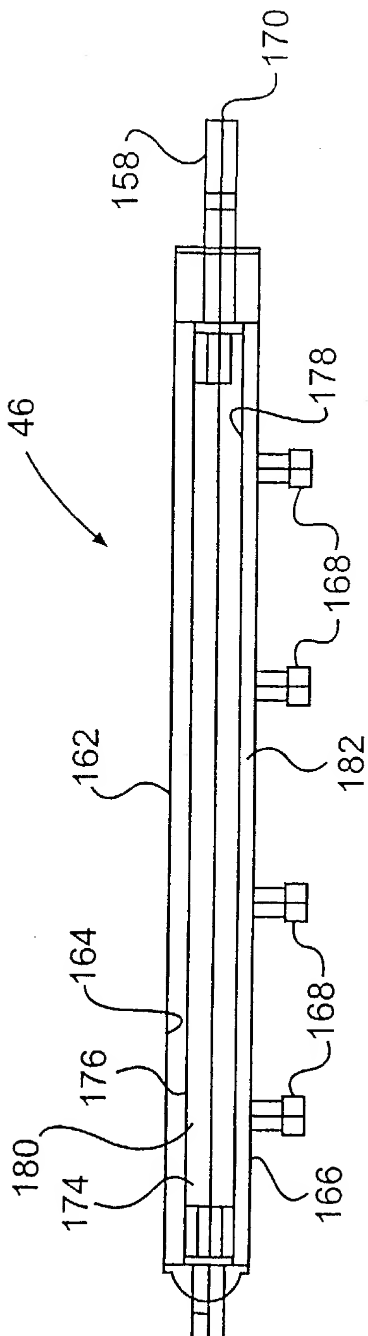

FIG. 8

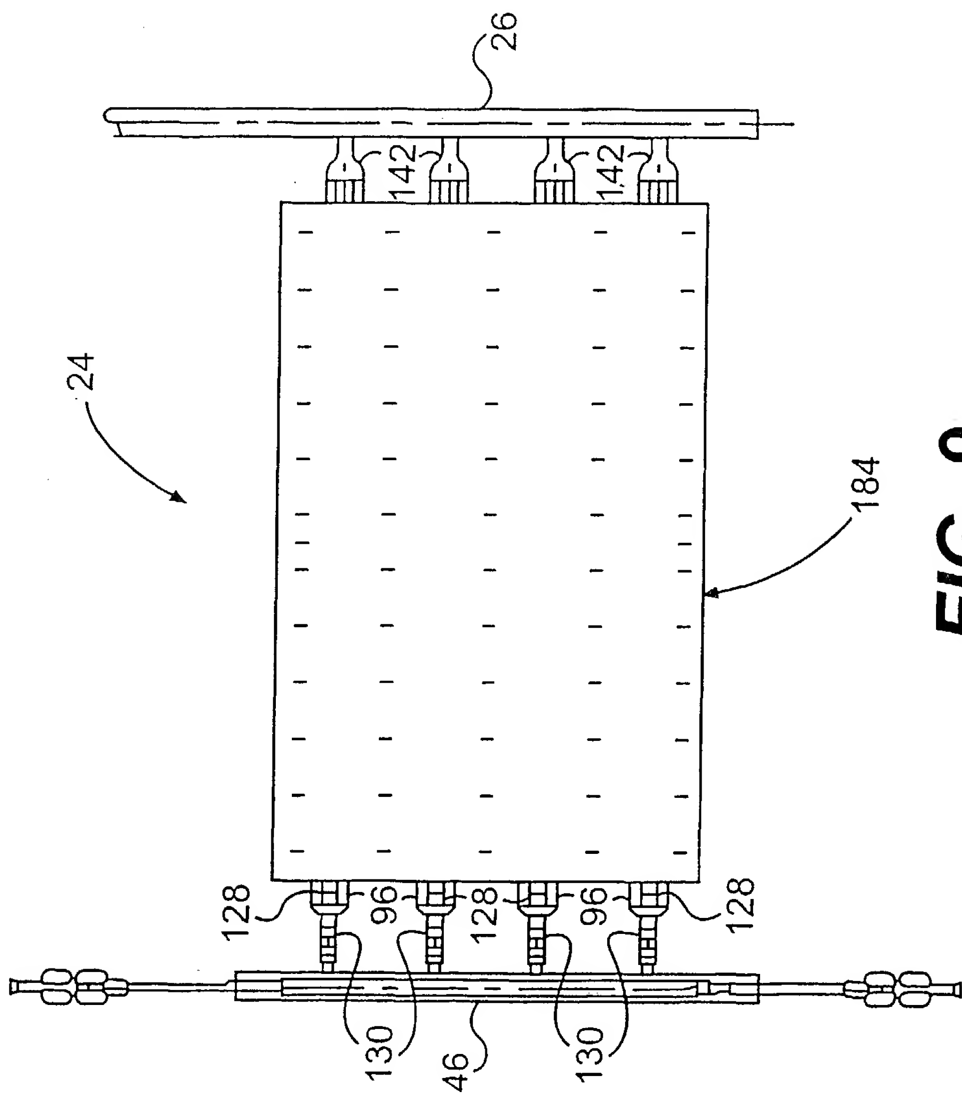

FIG. 9

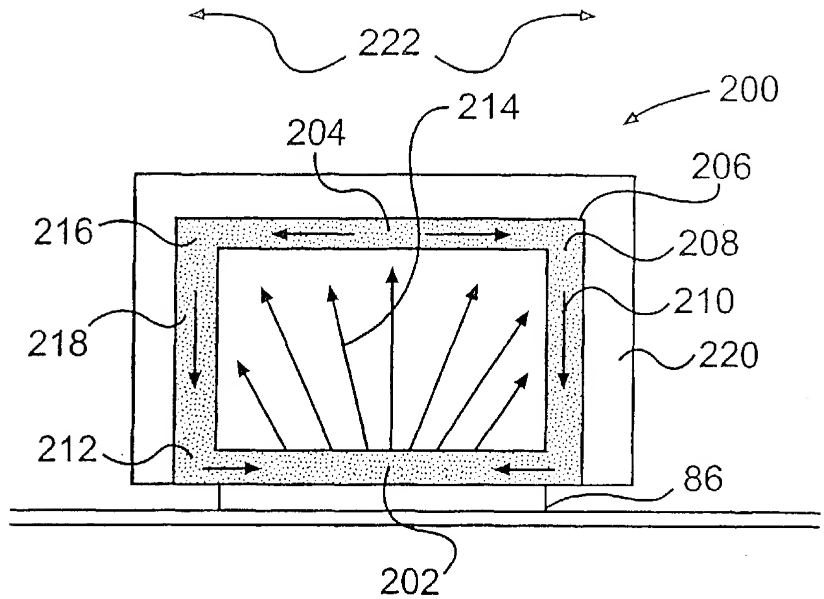

FIG. 10A

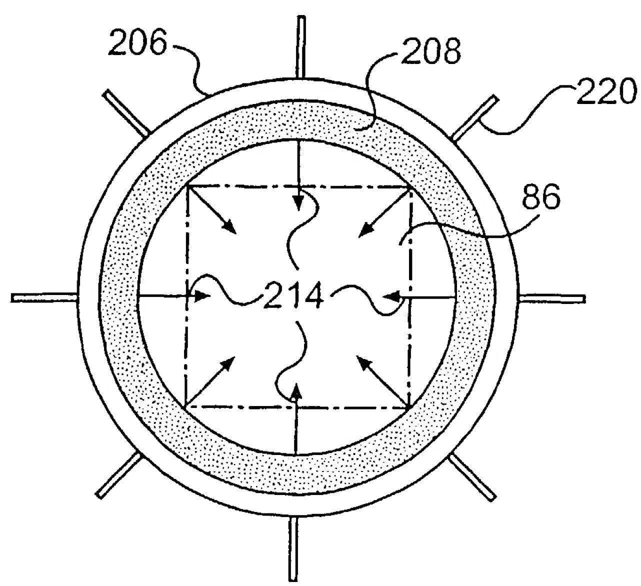

FIG. 10B

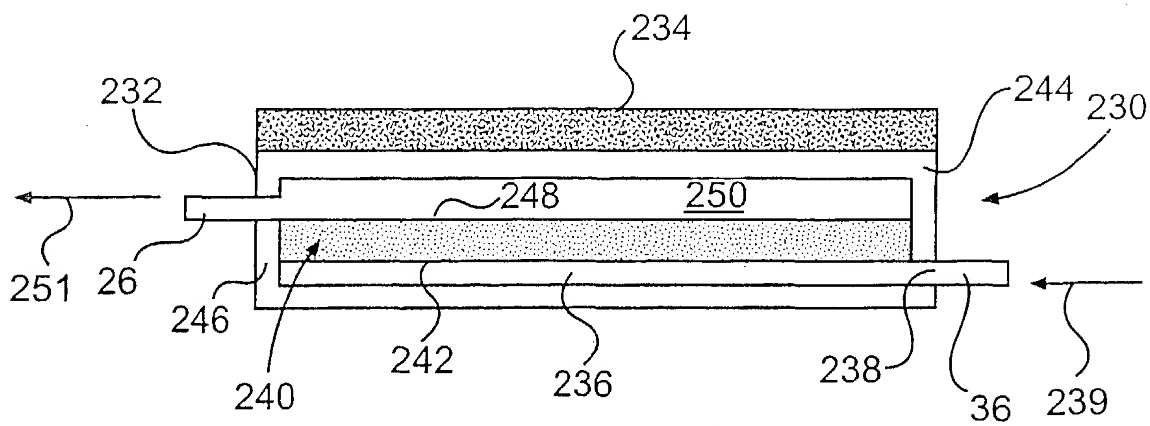
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FIG. 11

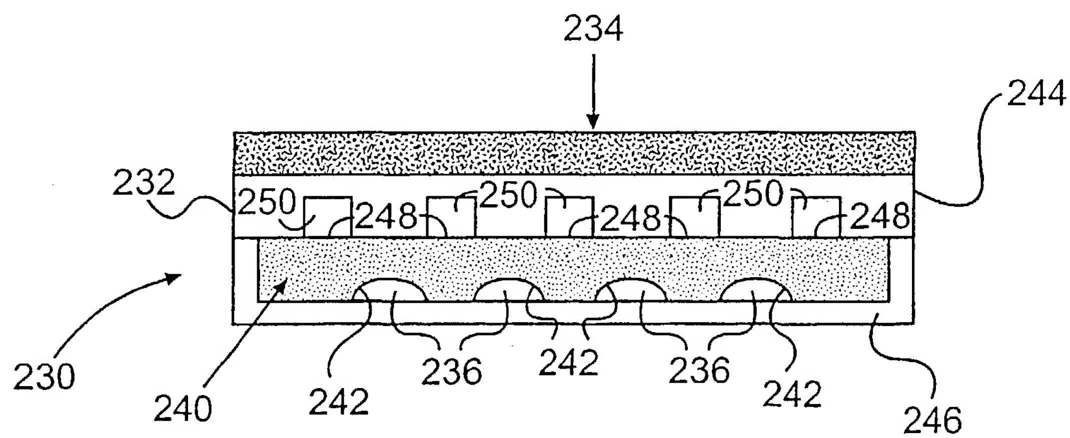
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FIG. 12